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Estimation and harvesting of human heat power for wearable electronic devices

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Abstract. The paper deals with the issue of self-powered wearable electronic devices that are capable of harvesting free available energy dissipated by the user in the form of human heat. The free energy source is intended to be used as a secondary power source supporting primary battery in a sensor bracelet. The main scope of the article is a presentation of the concept for a measuring setup used to quantitative estimation of heat power sources in different locations over the human body area. The crucial role in the measurements of the human heat plays a thermoelectric module working in the open circuit mode. The results obtained during practical tests are confronted with the requirements of the dedicated thermoelectric generator. A prototype design of a human warmth energy harvester with an ultra-low power DC-DC converter based on the LTC3108 circuit is analysed.

1. Introduction

Among different ubiquitous and free energy sources, such as: light, electromagnetic background, heat and vibrations, only the latter ones can be generated by human beings and next converted into useful electrical energy to supplying smart electronic devices, wireless sensor nodes, as well as wearable devices [1], [2]. Small and irregular pieces of human energy have to undergo harvesting processes which mostly require careful modeling and customized design of ultra-low power management circuits in order to increase the overall energy conversion efficiency [3], [4].

The feasibility study and specific needs of self-powered smart wearable devices should be confronted with available energy, therefore the performance of the human power sources have to be theoretically investigated and acknowledged in practice under experiments.

In our recent research work we have been conducting investigations toward self-powering sensor bracelet for monitoring important life parameters like pulse, respiration, and blood oxygenation. The bracelet is going to be equipped with an energy harvesting module converting available human warmth into electricity to support and prolong the life time of the primary battery. Figure 1 shows considerations on suitable locations for attaching the sensor bracelet; they need to take into account not only the comfort of the user, but also the available human heat power and easy access to measuring points of the life parameters.

The paper presents theoretical considerations on a method for estimation of heat power released by a human being during day-to-day activities, and then the results of practical measurements at different body locations. It is followed by a discussion on modeling of interfacing mechanical assembly and electronic circuit capable of converting ultra-low-power signals form energy harvester. The rating of

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the heat power is a useful indicator for wearable electronic devices that are to be powered with the energy harvested from human warmth, such as biomedical autonomous systems, healthcare sensors, etc.

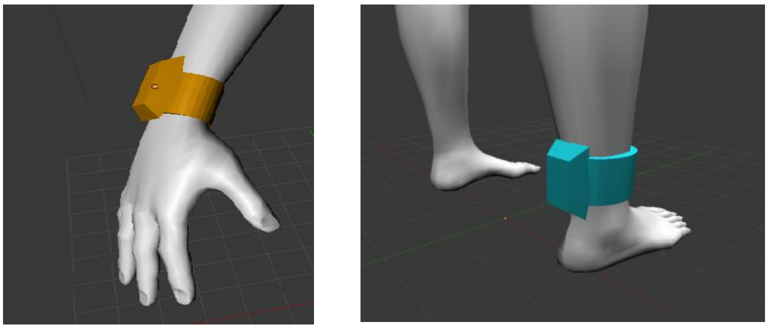

Figure 1. Different locations considered for attaching the sensor bracelet.

Harvesting of dissipated human heat energy has been investigated by many research teams for the recent years. A few successful demonstrators of autonomous energy sources made of tiny thermoelectric generators (TEG) were presented. They were next implemented to supplying body area networks and wearable sensors [5], [6].

Specifics of the human power sources as well as the design process of wearable harvesters entail laborious measuring and collecting of data, and also a careful process of electrothermal modeling and simulations. It is mainly due to the fact that human warmth harvesting process deals with an ultra-low power source which is additionally hampered by relatively low conversion efficiency. According to authors' calculations and simulations, the output electrical energy $P_{electrical}$ from TEG is equal only to about a few percent of the input human heat power Q_{human} taken from an unit of body area, which is shown in figure 2 [7].

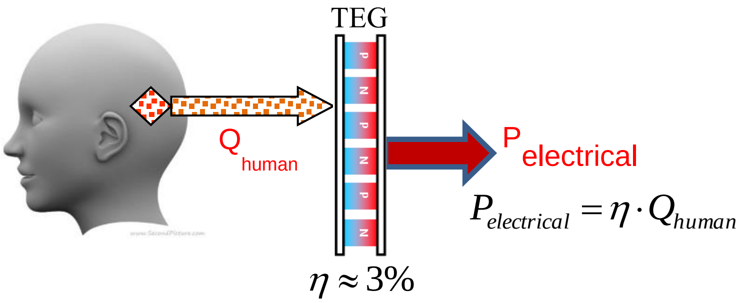

Figure 2. Human heat harvesting process.

2. Estimation of human heat power

Quantitative analysis of heat transfer in human tissues has been a subject of research work performed for last few decades; some highly detailed models have been obtained, suitable for implementation to numerical simulations [8]. Whereas the heat power dissipated by the humans differs between individuals and the location on the body area, the output electrical energy $P_{electrical}$ depends not only on the conversion efficiency η of the TEG. It is influenced heavily by the quality of the attachment of the TEG to the body too (which also includes thermal resistance of the skin), and the thermal resistance which is imposed on the human heat flow on the way from the TEG to the ambient (which can be expressed by thermal resistance of the heat sink).

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2.1. Electrothermal modeling

Apart from that thermoelectric modules are used as TEGs in target heat energy harvesting devices, they can also be applied to experimental estimation of human heat power when they are operating in open circuit mode. Heat transfer in human warmth harvesters attached to the body can be modeled as one-dimensional flow of human heat power Q_{human} through a series of thermal resistances: expressing attachment to the skin R_{th_attach}, thermoelectric generator R_{th_TEG}, and the heat sink $R_{th\_heatsink}$. The heat starts flowing at temperature T_{human}=36.6 ºC, and moves to the ambient at temperature T_a, which is depicted on the equivalent electrothermal model presented in figure 3.

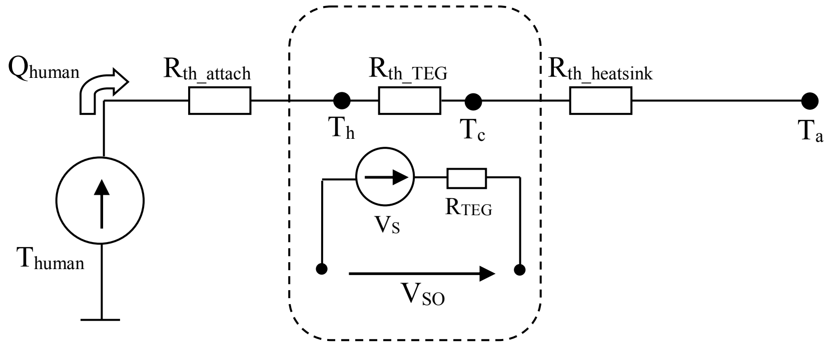

Figure 3. Equivalent electrothermal model for heat transfer and energy conversion analysis.

The heat power Q_{human} flowing through the TEG causes a temperature gradient ΔT_{TEG} across thermoelectric module's plates, and due to the Seebeck effect it generates a voltage V_S according to the formula (1).

$$V_S = \alpha \Delta T_{TEG} = \alpha (T_h - T_c) \tag{1}$$

where: α [V/ºC] is the total Seebeck coefficient for a given thermoelectric module, T_h and T_c [ºC] are the temperatures at the hot and cold plates of the TEG, respectively.

The Seebeck voltage is equal to the output voltage of the TEG working in open circuit mode (2). Moreover, the temperature gradient can be expressed as a temperature drop over the thermal resistance R_{th_TEG} , caused by the flowing heat power Q_{human} (3). Combining (1), (2) and (3), one can get the formula (4) for heat power, expressed by the measured open circuit Seebeck voltage.

$$V_{SO} = V_S \big|_{I_{TEG}=0} \tag{2}$$

$$\Delta T_{TEG} = Q_{human} \cdot R_{th\_TEG} \tag{3}$$

$$Q_{human} = \frac{\Delta T_{TEG}}{R_{th\_TEG}} = \frac{V_{SO}}{\alpha \cdot R_{th\_TEG}} \tag{4}$$

Although the Seebeck coefficient, as well as TEG thermal resistance, are strongly temperature dependent, we can assume that for wearable applications they are constant, thus the human heat power is proportional to the Seebeck voltage.

2.2. A testing setup and measurements

The testing setup for estimation of human heat power is presented in figure 4. The measurements were performed by means of Data Logger, with 16-bits A/C converter, and at 1ms time interval. It was collecting the Seebeck voltages from the thermoelectric generator under test and attached directly to the body surface. The TEG was composed of a commercially available thermoelectric module consisting of 127 thermopiles connected electrically in series and thermally in parallel, and the heat sink having thermal resistance of 2 K/W. The surface area of the TEG directly attached to the skin was a square 4cm x 4cm.

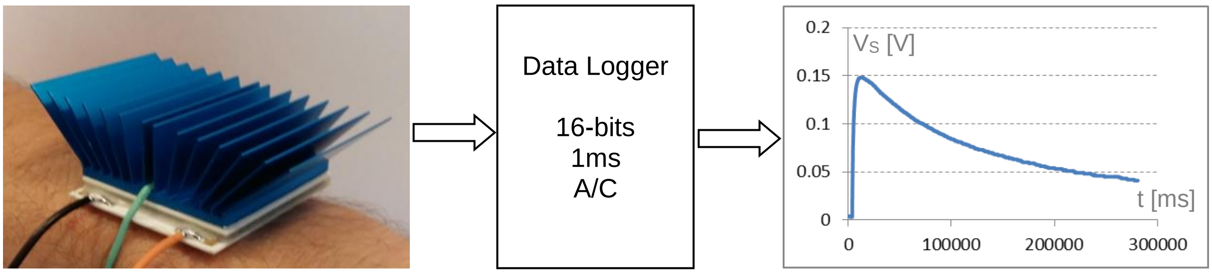

Figure 4. Testing setup.

In table 1, a series of V_{SO} measurements at steady states, and calculated ΔT_{TEG}, Q_{human}, and R_{th_attach} in different locations of the body area is shown. For estimation of constant coefficients α and R_{th_TEG} we used previously evaluated electrothermal model of the thermoelectric module and the temperature characteristics for Seebeck coefficient α and the thermal conductance λ (which is in fact the reciprocal of the R_{th_TEG}) [9]. From figure 5 it is evident that for considered very small temperature range around T=35°C: α=51.75 mV/K, and R_{th_TEG}=2.28 K/W

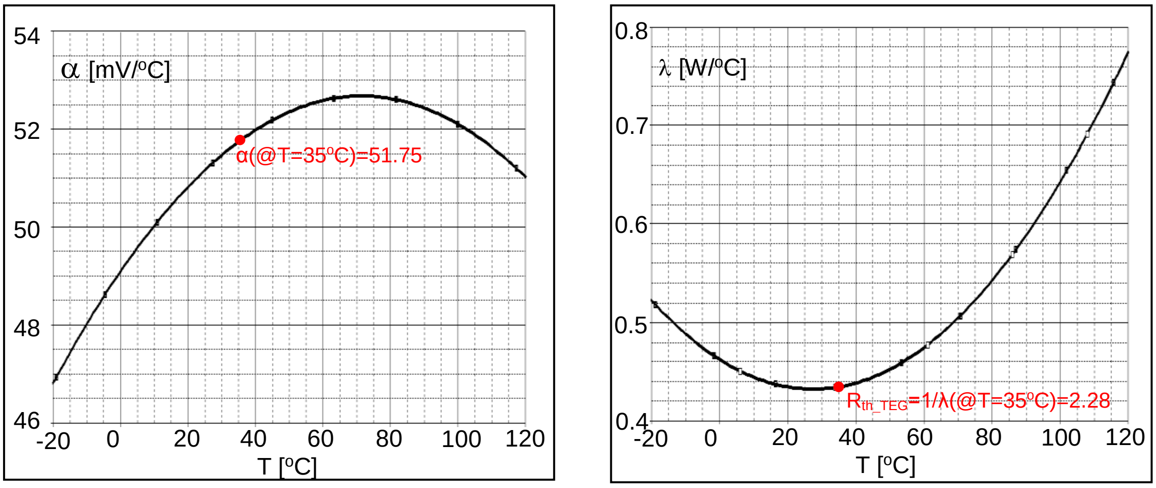

Figure 5. Temperature characteristics of the Seebeck coefficient α, and the thermal conductance λ.

Table 1. Measured open circuit voltage and calculated: temperature gradient, heat power, and attachment thermal resistance at different locations of the human body (surface area of the thermoelectric module is 40 mm x 40 mm).

Attachment	V_{SO} at steady state [mV]	ΔT_{TEG} [°C]	Heat power Q_{human} [mW]	R_{th_attach} [K/W]
wrist up side	10.0	0.19	80	115.0
wrist down side (close to artery)	13.1	0.25	110	86.8
forehead	14.7	0.28	112	76.9
leg	8.0	0.15	70	144.9
arm	11.2	0.22	90	102.3

The measurements took place at ambient temperature T_a=26.5 °C; for estimation of the R_{th_attach}, we assumed T_{human}=36.6 °C. The results shown in table 1 met our expectations to some extent. The highest levels of heat power were generated in a close proximity to the artery and the head. On the other hand the highest attachment thermal resistance is observable under the muscles and adipose tissue. If the average human body surface is 1.8 m^2, and assuming an average heat power dissipating on a 16 cm^2 TEG surface in the range of 100 mW, it would mean that the human being is dissipating by his skin more 100 W of the heat power at resting position.

3. Harvesting of human warmth and converting into electricity

Even if the thermoelectric generator can provide reasonable power harvested from the human warmth, the main difficulty (regarding its utilization) manifests in converting an ultra-low Seebeck voltage to a level that is necessary to supplying electronic circuits and sensors.

One of the most suitable electronic integrated circuits, with the lowest input voltage, is offered by Linear Technology. DC-DC LTC3108 converter can be applied directly to a very low voltage sources; the only limitation is that the minimum required input voltage under operation is 20 mV. It means that the open circuit Seebeck voltage should be at least 40 mV (under operation, the internal resistance of the TEG is matched with input resistance of the converter).

A feasibility study shown below reveals some hints and limitations when human heat harvesting is considered. During simulation experiments we used an accurate electrothermal model of the thermoelectric module implemented into electronic circuit simulator LTSpice, and we also assumed that the TEG is attached to a wrist close to the artery.

Figure 6 shows the simulation setup. All the external conditions (ambient and human body temperatures) were set to the same values as when the measurements were performed. For the first case we applied a variable thermal resistance instead of estimated earlier R_{th_attach}=86.8 K/W; its value was swept by ‘control’ signal. Our intention was to determine a relation of the Seebeck voltage against thermal resistance of the attachment, which was presented in figure 7.

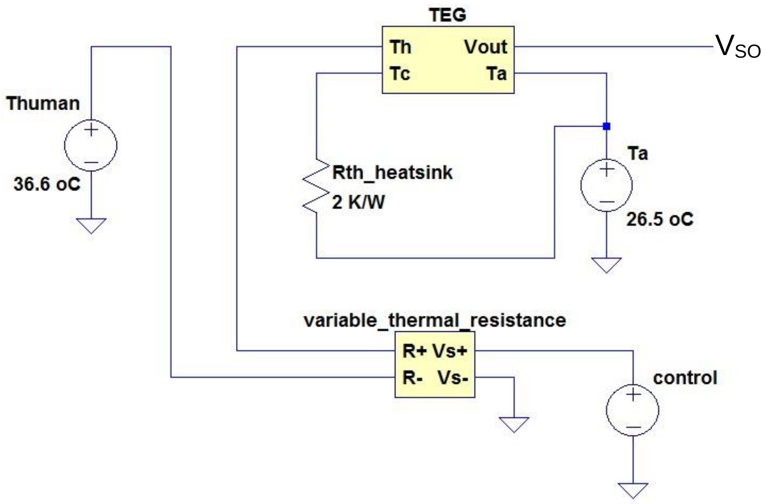

Figure 6. Scheme of the simulation setup for determination of the Seebeck voltage relation against the thermal resistance of the attachment.

As it could be expected, the quality of the attachment of the TEG to the body strongly influences on the output Seebeck voltage. The required minimum voltage needed to start the converter could be attained if the thermal resistance R_{th_attach} had been decreased to 25 K/W. Another option of increasing the output voltage is the heat sink. But as it is shown in figure 8, decreasing the $R_{th\_heatsink}$, even to the extreme low level, only slightly improves the V_{SO}.

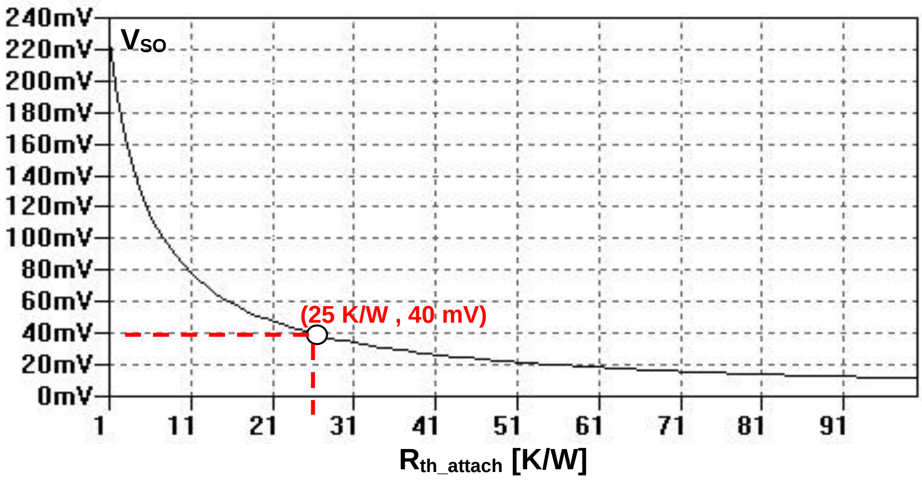

Figure 7. Open circuit Seebeck voltage against thermal resistance R_{th_attach}.

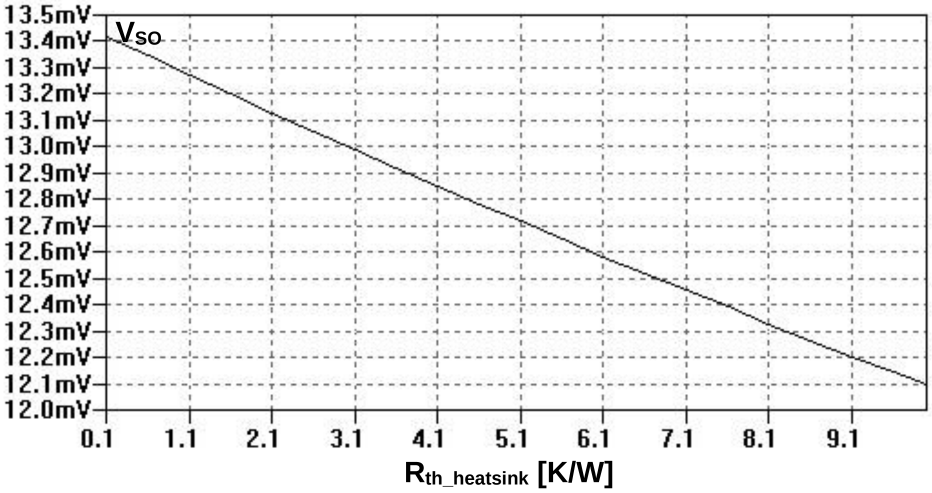

Figure 8. Open circuit Seebeck voltage against thermal resistance $R_{th\_heatsink}$.

At the end we performed experiments on a setup shown in figure 9, which was combined of the thermal part – the model of the TEG, and the electrical one – the boost-up voltage converter.

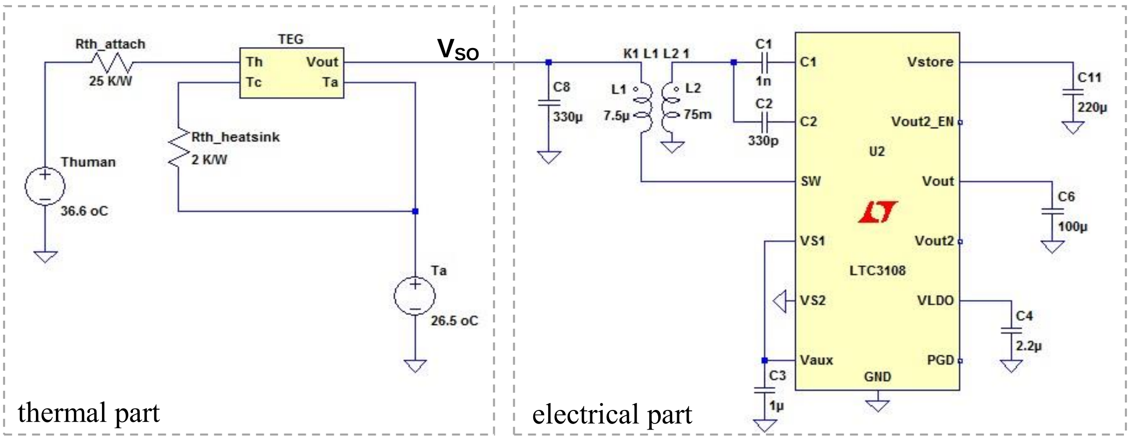

Figure 9. Setup for combined simulations with boost-up voltage converter.

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Our goal was to prove that by lowering the attachment thermal resistance to 25 K/W, the LTC3108 converter could be triggered by the very low output Seebeck voltage. From the figure 10 it is evident that for presumed case, the converter circuit is able to deliver a regulated constant voltage at its output VLDO=2.2 V.

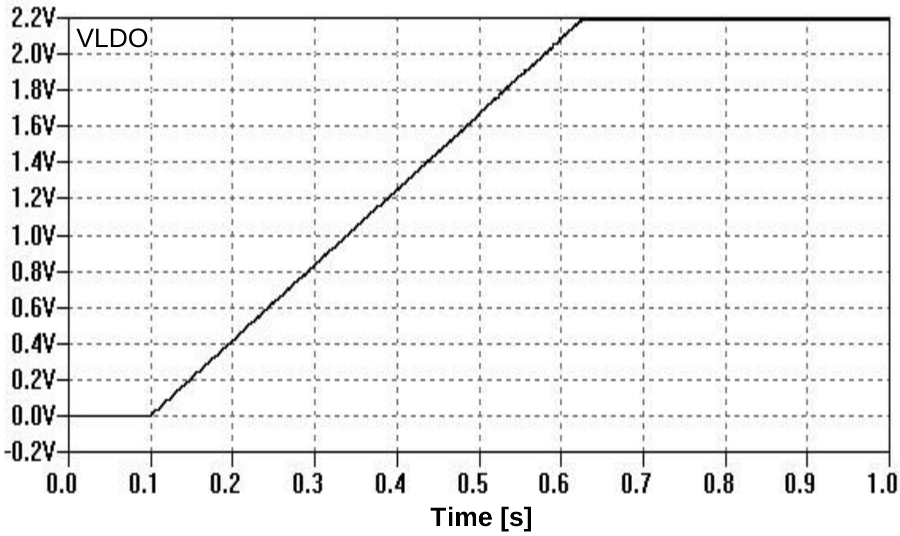

Figure 10. Regulated output voltage from the converter supplied by human heat.

4. Conclusion

In the paper a whole process of investigations toward a prototype human warmth harvester was described. The measured values of heat power sources and attachment thermal resistances in different points of the body area were confronted with the requirements of the commercially available ultra-low voltage converter, namely with its required minimum start-up input voltage. It should be noted that we considered only steady states (TEG working in equilibrium), therefore the stable output Seebeck voltage was much lower than the maximum levels observed during transient states (for example, right after attaching the TEG to the body). Due to the relatively large thermal time constants, reaching the equilibrium by the whole harvester assembly takes a few hundreds of seconds in the case of the tested TEG.

During the experiments on a real circuit with LTC3108 we observed that it was able to deliver a regulated VLDO=2.2 V for a while, which next disappeared in the thermal equilibrium. The output Seebeck voltage could sustain operation of the converter only in the thermal transient state, right after attaching the TEG to the wrist. It was mainly due to a thermal capacitance of the heat sink, whose temperature was getting higher as the heat was flowing from the body through the TEG to the ambient, thus at the same time lowering the temperature gradient at the plates of the thermoelectric module, and in consequence decreasing the Seebeck voltage below the minimum start-up level required by the LTC3108.

The presented combined electro-thermal models indicate that for a given single thermoelectric module and external conditions, namely the human and ambient temperatures, the only possible way to increase the output Seebeck voltage is improving (lowering) the attachment thermal resistance, which appeared higher in the experiments than we expected. We suspect that due to a very thin TEG plate that was attached directly to the skin, the human heat could leak to the upper plate, thus creating some path allowing the heat flux to bypass the TEG. Another natural solution to achieve required higher output Seebeck voltage in the thermal equilibrium is connecting more thermoelectric modules in series.

5. References

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